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Theory and Practice of Bicycle Race-Track Construction

Civil Engineering
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THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

Horatio Weber Baker

ENTITLED Theory and Practice of Bicycle Race-Track Construction

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE DEGREE

OF Bachelor of Science in Civil Engineering

Ira O. Baker.

HEAD OF DEPARTMENT OF Civil Engineering

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BICYCLE RACE-TRACKS

With the extended use of bicycles has come a relatively small class of people who choose bicycle racing as a recreation or even a profession. From these riders has come a demand for tracks built espiciallŷ for bicycle racing. It is the purpose of this thesis to enquire into the theory and practice of bicycle race-track construction.

The design of a track may be considered under three heads: first, the ground plan; second, the banking or superelevation of the outer edge; and third, the material to be used in the construction.

I. GROUND PLAN

The following principles must be borne in mind in the design for the ground plan of a bicycle race-track.

1. The length and form of the track will depend upon the size and shape of the area

UIUC

2. Large tracks are expensive to construct, and and do not afford the spectators a good view of the racers. Very small tracks are objectionable because of the sharp curvature and consequent high banking.

3. For convience it is desirable that the length of the track shall be an aliquot part of a mile. The length of all bicycle tracks is measured on a line eighteen inches from the inner edge of the track, called the pole line.

4. The field should not be so wide that the spectators are unable to see easily all parts of the race.

6. The curves should be of such form that the rider experiences no lurch due to change of direction in following the curve.

7. On curves a superelevation of the outer edge is required. Since the superelevation can not be effected instantly, a varying curvature must be used to permit the joining of the flat tangents with the fully banked curves.

The conditions which best meet

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the first four requirements can be determined only by experience, while the conditions meeting the remainder may be determined by mathematical analysis. It is proposed to describe the more noted tracks with a view of determining the present status of the best practice, and then to design a track which shall fully meet all of the requirements.

Present Practice

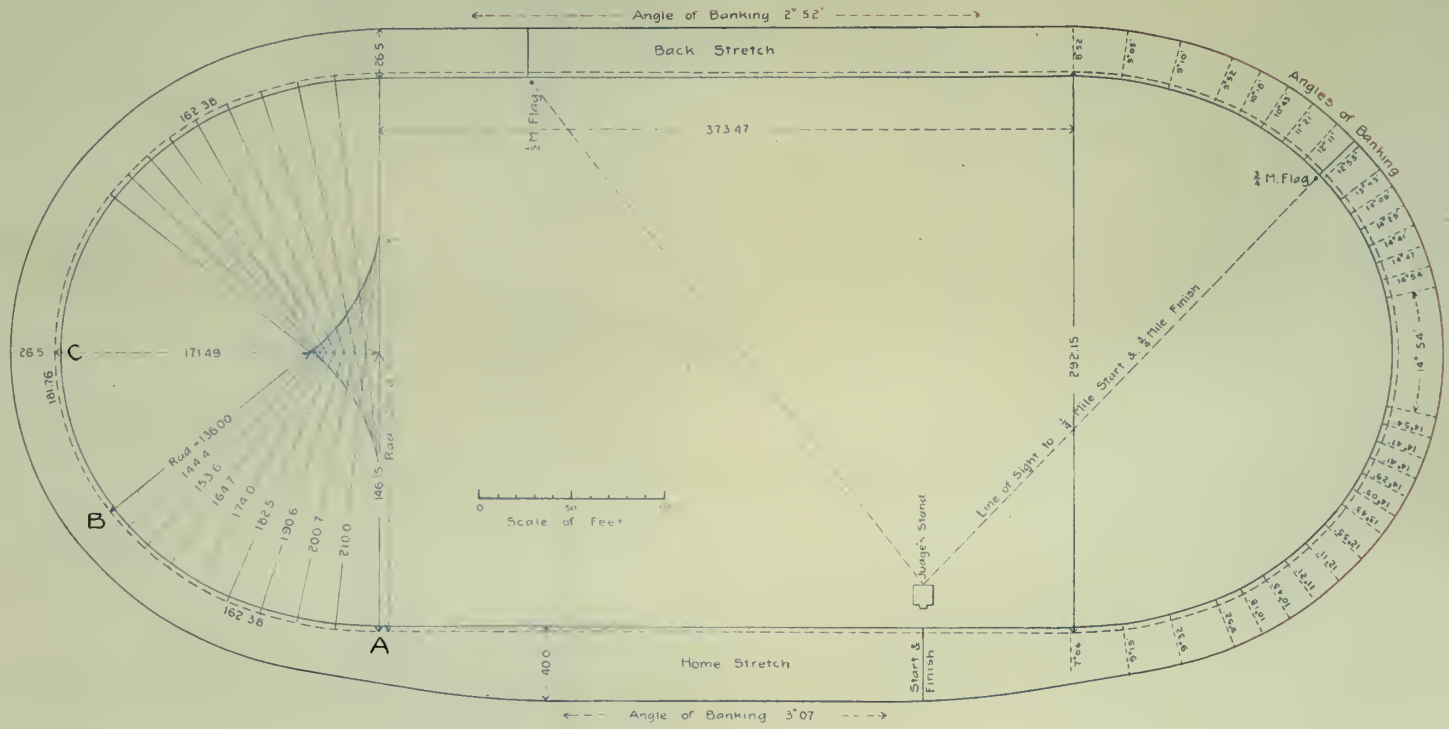
The first tracks were very crudely laid out. For example, it is stated that the curves of one of the earliest tracks in the country, the one half mile track at Hampden Park, Springfield, Mass. were located by running a bicycle over the ground and staking out the trail.

Most of the early tracks were semi-circles connected by tangents. Among these are the ones at Waltham, Mass., and Louisville, Ky. Each is one third of a mile in length with semi-circles of 150 feet radius and tangents 409 feet long. The tracks have each held many world's records

and were for a time very popular.

In 1896 Mr. C. E. Hawley, then consulting engineer of the Pope Manufacturing Co., designed and constructed the famous Manhattan Beach track. This seems to have been the first attempt to meet scientifically requirements 6 and 7 stated above. This track is one third of a mile in length and consists of two tangents connected by "elliptical curves" to circular arcs (see Fig. 1, p. 5). Apparently the elliptical curve, AB, consists of a series of nine circular arcs, each 6° long, having radii ranging in length from 212 to 144 feet. The circular arc, BC, is 38°17' long and has a radius of 136 feet. The tangents are 373.47 feet long, the elliptical curves 162.4 feet long, and the circular arcs 90.9 feet. The track is 26.5 feet wide save the home stretch which is 40 feet — the widest track in the country.

In 1897 a quarter mile track was constructed at Racine, Wis., of exactly the same ground plan as the Manhattan



ONE THIRD MILE TRACK
AT
MANHATTAN BEACH
LONG ISLAND NEW YORK

FIG. 1.

track except that the tangents were shortened.

The Charles River track Boston Mass. is one third of a mile in length, the circular curves being joined to the tangents by easement curves consisting of compound circular arcs. This track is a later design by the designer of the Waltham track, and may be considered as showing in the mind of the designer at least, the importance of joining the tangents and curves by arcs of varying radius.

In 1896 the well known track in Garfield Park Chicago was constructed according to the design and under the direction of Mr A. C. Sanders, the Engineer of the West Park Board. The track is one half mile in length with tangents 396.5 feet long connecting semi-circular arcs having radius of 300.32 feet (see Fig. 2 p. 7). The track is 25 feet in width save the home stretch which is 35 feet. The widening of the home stretch was accomplished by moving the center for the arc AB

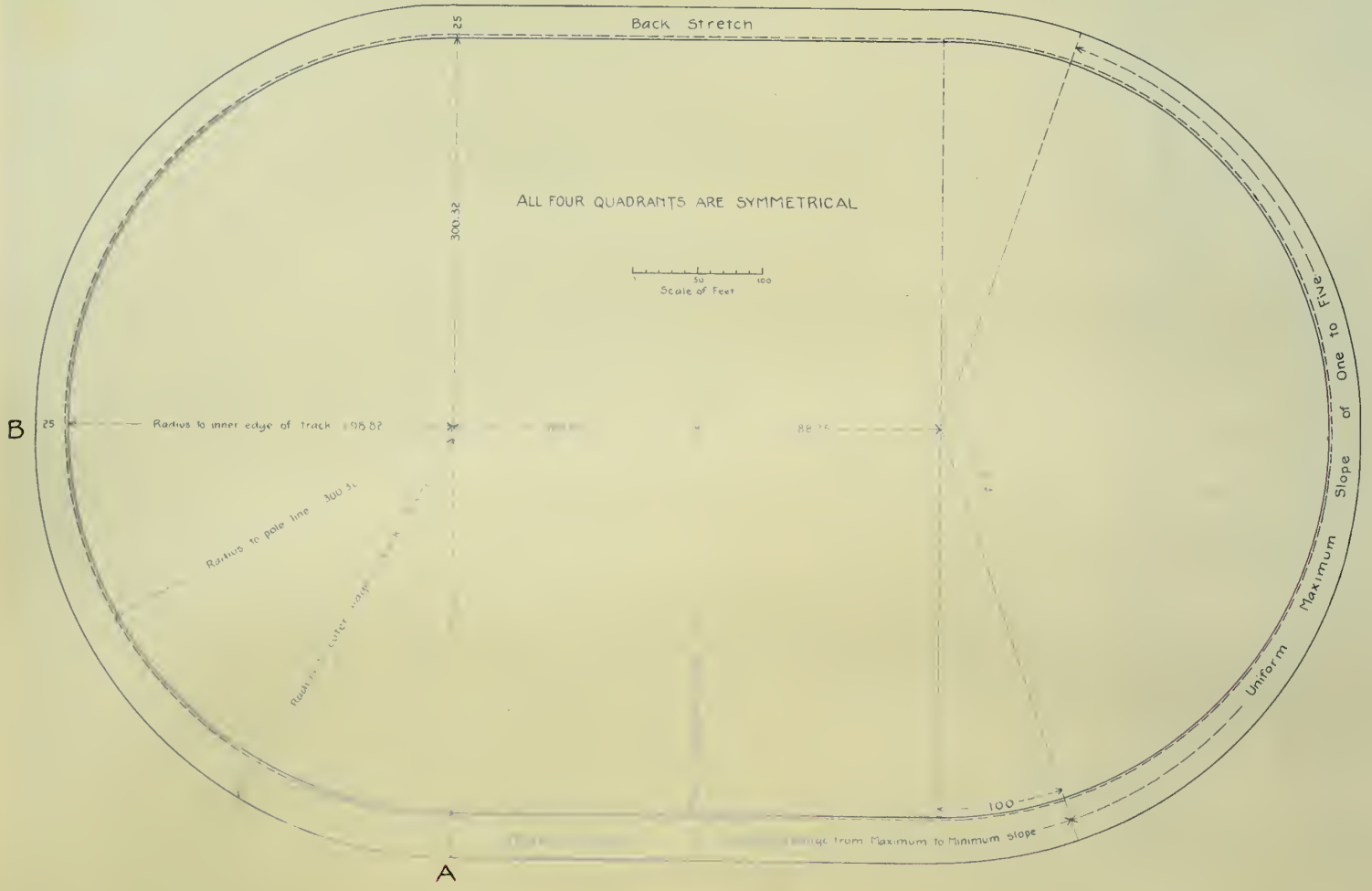

Back Stretch
25
300.32
ALL FOUR QUADRANTS ARE SYMMETRICAL
1
50
100
Scale of Feet
B
25
Radius to inner edge of track
Radius to pole line
Uniform Maximum Slope of One to Five
100
A

FIG. 2.

10 feet toward the home stretch.

These examples represent the most advanced theory of the form of bicycle race-tracks since almost all others have been built by carpenters or professional riders without reference to the principles involved.

Correct Form

The length and form of the track will depend upon the size and shape of the area available. However these factors will vary so greatly that they can not be considered in a general design; and hence it will be assumed that the area available is unlimited.

Length. Mr. Hawley, probably the best authority on bicycle tracks in this country, states in a private communication, that in his opinion the ideal track should be four laps to the mile. In view of this statement and of the reduced cost over a larger track, the design will be made for a track one fourth of a mile in length.

Proportions of Field. To determine the relation between the length and breadth of the field of those tracks which may be considered as the best representatives of current practice, Table I was computed. The track called "Hawley" is the ideal form suggested by Mr Hawley in the communication above referred to.

TABLE I

PROPORTIONS OF FIELD

REPRESENTATIVE OF BEST CURRENT PRACTICE

Arranged in order of Roundness

Ref. No.	Name of Track	Length of Field	Width of Field	Ratio	Length of Track	Width of Field	Ratio
1	Garfield Park	976.5	600	0.614	2640	600	0.227
2	Racine	499.6	295	0.590	1320	295	0.223
3	Hawley	519.6	275	0.529	1320	275	0.209
4	Waltham	709.0	300	0.423	1760	300	0.170
5	Manhattan	715.5	295	0.410	1760	295	0.168
			Mean	0.513		Mean	0.199

From a study of the table we may conclude that a track to meet the requirements of current practice should have a field about twice as long as wide, or width of field about one fifth of the length of the track. A field of these proportions will

give a track affording the spectators a good view of all parts of the race.

Form of Curves. In Fig. 3 the black line represents a portion of the pole line of a track consisting of semi-circles connected by tangents. A racer riding in the direction indicated, upon arrival at B, the

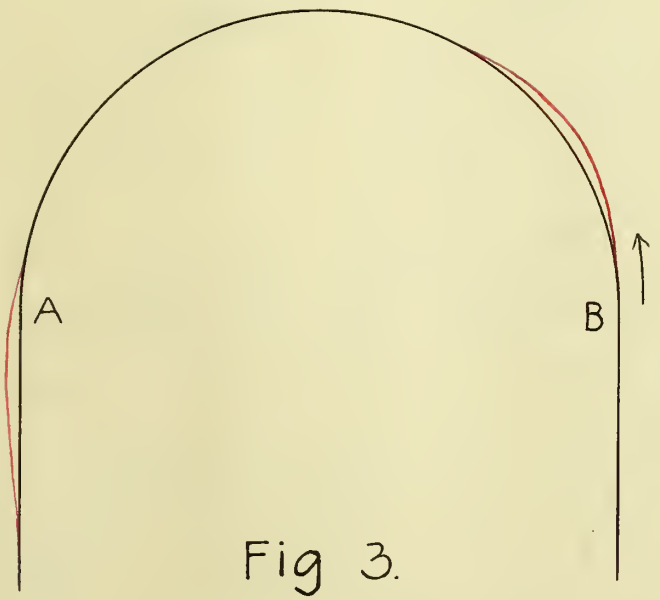


Fig 3.

point of tangency, will not be able to change instantly from a straight path with an infinite radius to a curved path with a uniform finite radius; but will involuntarily take a curvelinear course having a uniformly decreasing radius. Similarly in entering a tangent from a curve, the rider will swing out from

the pole line of the tangent to a curve of increasing radius. The red line of Fig. 3 shows the path involuntarily taken by the rider. Since all distances are measured on the pole line, and since all excess distance ridden adds to the time of the race, there is a decided advantage in having the pole line of the same curvature as that of the path naturally taken by the rider. The greater ease with which a wheel can be guided around a curve of gradually varying radius also adds to the speed of the race.

For reasons which will be discussed later, the surface of the track in curves should be elevated at the outer edge. This superelevation varies inversely as the radius of curvature. Since it is impossible to change instantly from flat tangents to banked curves, a track consisting of semicircles and tangents will not permit the proper superelevation of the outer edge. If, however, the tangent is connected to the circular arc by a curve of uniformly varying curvature, the banking in-

creases gradually from zero on the tangent to the full amount at the beginning of the circular arc.

The Transition Spiral* deduced by Prof. A. N. Talbot is a curve of uniformly increasing radius which has been much used on railroads in recent years as an easement curve, and seems particularly adapted to bicycle race-tracks. According to Professor Talbot's definition, "The transition spiral is a curve whose degree of curve increases directly as the distance along the curve from the point of tangency." Without entering into a discussion of the mathematical relations of the curve, the writer will endeavor to apply the principles of the spiral to the design of the ground plan for a quarter-mile bicycle race-track.

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* For an elaborate treatment of this curve see "The Transition Spiral" by Arthur N. Talbot in Technograph No. 5 (p. 71); reprint of same with additions, in Technograph No. 13 (p. 74. Also published separately by the author 4" x 6½" paper, pp. 64.

The following notation will be used, being that given by Professor Talbot.

P.S. = point of spiral, i.e., the point of tangency of the spiral and the tangent.

P.C.C. = point where the spiral compounds with the circular curve.

R = radius of curvature of the spiral at any point.

D = degree-of-curve of the spiral at any point; called D_1 for the P.C.C.

a = rate of change of the degree-of-curve of the spiral per 100-ft. station. It is the degree-of-curve of the spiral at 100 feet from the P.S.

L = number of 100-ft. stations from the P.S. along the curve to any point on the spiral; called L_1 for the whole spiral.

Δ = angle between the initial tangent and the tangent the spiral at any point; called Δ_1 for the whole spiral.

Θ = deflection angle at the P.S., from the initial tangent to any point on the spiral; called Θ_1 for the whole spiral.

X = abscissa of any point on the curve referred to the P.S. as the origin, and to the initial tangent as the axis of X.

Y = ordinate of the same point measured at right angles to the above axis.

Having decided that the track shall consist of circular arcs connected to tangents by transition spirals, it is necessary to determine the dimensions of the spiral and the circular curves. Only one of the quadrants of the track need be considered since all are symmetrical. The pole line of a quadrant will be 330 feet in length. In Fig. 4 this quadrant is represented by

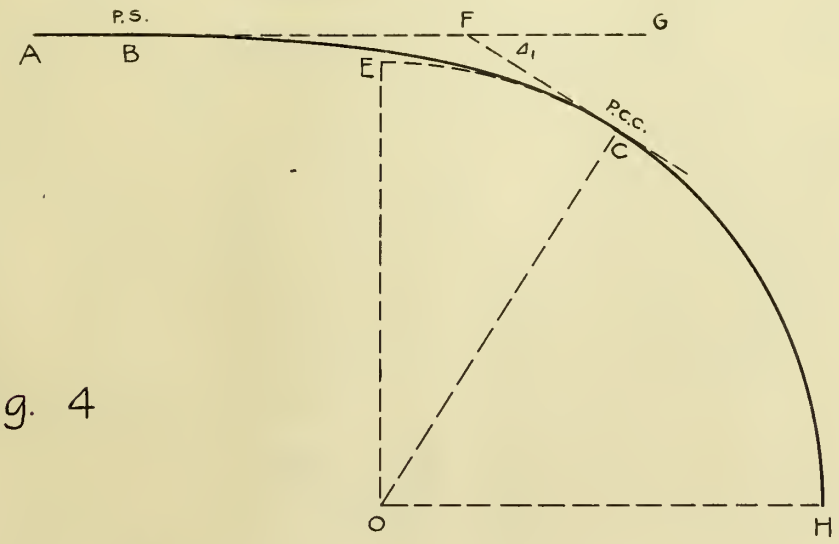


Fig. 4

ABCH of which AB is a tangent, BC the

transition spiral, and CH a circular arc. In order to give sufficient tangent upon which to start races, the length of the tangent AB will be taken at 30 feet. In reality there will be about twice this amount of practically straight track, since the change of direction of the first 25 feet of the spiral will be less than one half a degree.

The problem now is to determine the value of Δ_1 and the radius of the circular arc. The length of the combined curves being known, an expression for this length will be deduced in terms of the unknown quantities.

The length of the circular arc is $\frac{I}{D}$, I being the intersection angle COH, and D the degree-of-curve of the arc. From similar triangles, the angle GFC = the angle EOC; and since GFC is Δ_1, $I = 90° - \Delta_1$. Also D of the circular arc = D_1 of the transition spiral, and hence the length of the circular arc is

$$\frac{90° - \Delta_1}{D_1} \qquad \text{(1)}$$

The length of the transition spiral

is obtained from the formula $\Delta_1 = \frac{1}{2} D_1 L_1$, and is equal to

$$\frac{2\Delta_1}{D_1} \qquad \text{---------- (2)}$$

Adding (1) & (2) and equating the sum to the known length of the combined curves, expressed in 100-ft stations, we have:

$$\frac{90 + \Delta_1}{D_1} = 3.0 \qquad \text{---------- (3)}$$

Equation (3) having two unknown quantities is indeterminate, and hence of the quantities must be assumed. The circular curves of the Manhattan track with a radius of 136 feet have proved themselves fairly satisfactory. Curves with much shorter radii could not be used, because of the high banking required; and in order to be on the safe side a radius of 140 feet will be used for the circular curves. Since $D_1 = \frac{5729.65}{R}$, therefore if $R = 140$ feet, $D_1 = 40°926$. Using this value of D_1 in equation (3) gives $\Delta_1 = 32.°778 = 32° 46.7'$. Then knowing Δ_1 and D_1 the spiral becomes determinate.

The spiral may be located in the field in either of two ways; namely by deflection angles from the initial tangent, and chords measured along the curve; or by offsets from the tangent produced.

The curve deduced above is that of the hole line — the line on which distances are measured — but this line is not marked in the field. For convenience of construction, the inside edge of the track is the line that is staked out; and it is customary to have this line 18 inches from the hole line. The radius of the inside curve will be 18 inches less than that of the hole line, and hence D_c will be a trifle larger; but the transition spiral for the inside edge of the track will have the same Δ_c as that for the hole line. In Tables II and III, page 18, the data are given for laying out this spiral by the two methods mentioned above.

Fig. 5, page 19, shows the complete design. The track is 25 feet wide except the home stretch, which is 35 feet. Since the form of the outside

TABLE II

CHORDS AND DEFLECTION ANGLES FOR LOCATING THE SPIRAL FOR THE INSIDE EDGE OF THE TRACK

Point on Spiral	Distance from the P.S. along the curve	Deflection Angle at the P.S. from the Initial Tangent
P.S.	0.0 Feet	0° 00'
1	25.0	0° 16'.3
2	50.0	1° 05'.2
3	75.0	2° 27'.0
4	100.0	4° 21'.0
5	120.0	6° 15'.6
6	140.0	8° 30'.7
P.C.C.	158.47	10° 53'.7

TABLE III

RECTANGULAR COORDINATES FOR LOCATING THE SPIRAL FOR THE INSIDE EDGE OF THE TRACK

Point on Spiral	Distance from the P.S. on the Tangent Prolonged	Offset Perpendicular to the Tangent
P. S	0.00 Feet	0.00 Feet
1	25.00	0.12
2	49.98	0.95
3	74.88	3.20
4	99.48	7.57
5	118.71	13.03
6	137.18	20.55
P.C.C.	153 20	29.53

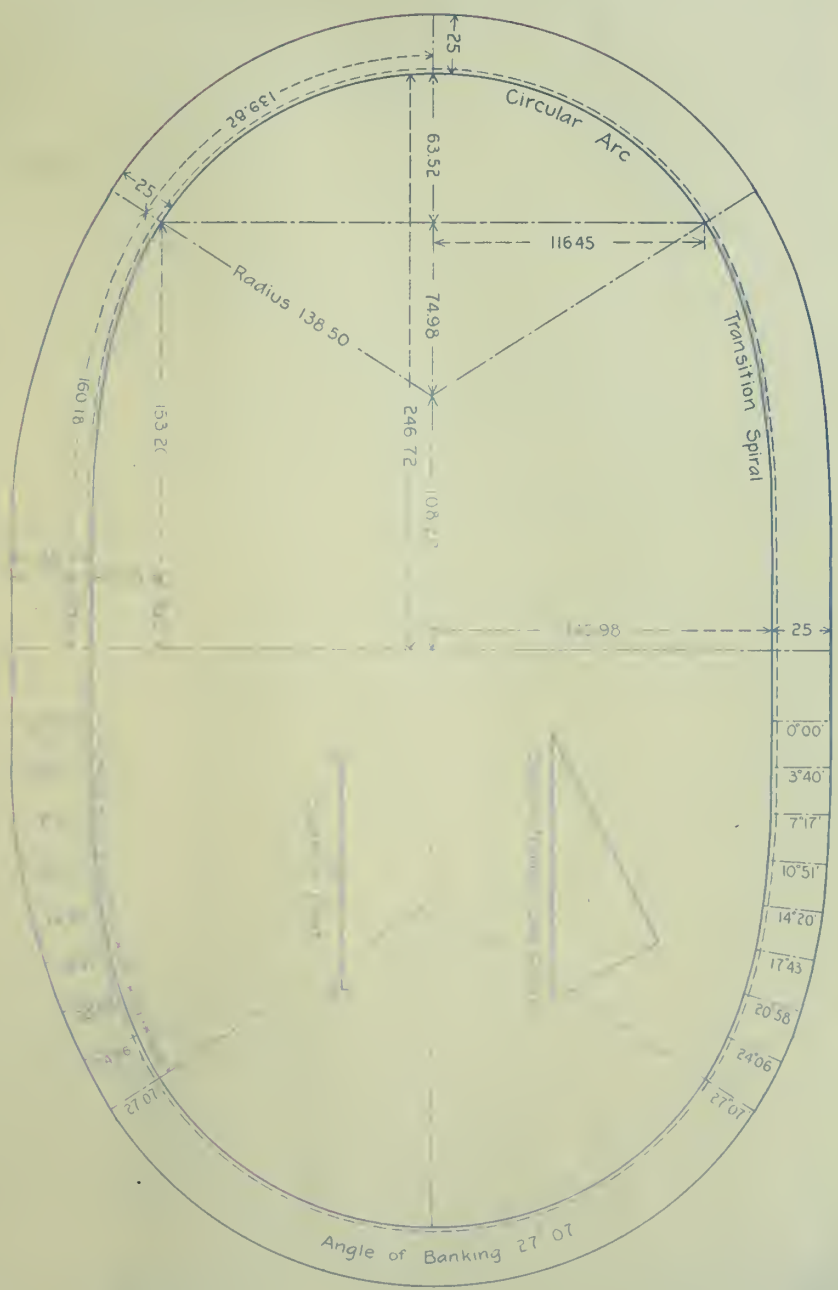

25
139.82
Circular Arc
63.52
25
116.45
Radius 138.50
74.98
Transition Spiral
160.18
153.21
246.72
108.27
140.98
25
0°00'
3°40'
7°17'
10°51'
14°20'
17°43'
20°58'
24°06'
27°07'
10.12
Angle of Banking 27°07'

FIG. 5.

edge of the track is not important it may be located by measuring from the stakes set on the inside edge.

The field is 0.5/2 of a mile in length. It is a little nearer round than the mean of the tracks previously cited; but if the field were made narrower the curvature would be sharper. Curves with a large radius are of more importance than a narrower field.

The above design meets all the requirements stated on pages 1 and 2; and possesses some important features new in bicycle race-track construction.

2. BANKING

According to the principles of mechanics the force required to deflect a body from a rectilinear path is:

$$\frac{MV^2}{\rho} \text{ or } \frac{WV^2}{g\rho}$$

in which

M = mass of the body,
V = velocity in feet per second,
ρ = radius of curvature,
W = weight of the body,
g = acceleration due to gravity, in feet per second = 32.16.

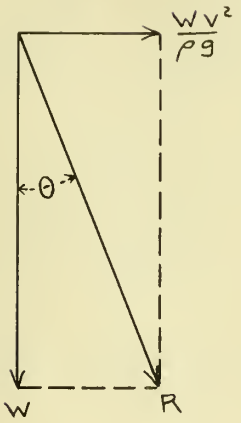
This force acts radially in the plane of the curve; and since the path of a body on a bicycle track is a curve whose plane is horizontal, this force acts horizontally.

The rider is acted upon by two forces — gravity and centrifugal force. These forces and their resultant are shown in Fig. 6, p. 22.

If the resultant is normal to the surface of the track, practically no effort

of the rider will be required to balance his wheel and hence he can give his entire attention to steering the sled. The resultant

Fig. 6.



will be normal to the surface of the track, if the surface makes the same angle with the horizontal that the resultant makes with the vertical. From fig. 6, we see that

$$\tan \theta = \frac{V^2}{\rho g} \qquad (1)$$

This formula gives the relation between the angle of inclination, the velocity, and the radius of curvature.

Having the design of the ground plan the radius of curvature will be known; but since the banking depends upon the velocity, the track must be designed for some particular speed. In deciding upon the velocity to be adopted, it is necessary to

determine whether the maximum or mean velocity shall be employed. If the track is to be used chiefly for races ridden against time, the maximum velocity should be adopted; but if for miscellaneous racing, the superelevation should be designed for the average velocity. To determine the practice in this respect, the banking of the more noted tracks will be investigated.

In the early tracks high banking seems to have been avoided for two reasons: first, because of a baseless prejudice against it; and second, because many of the races ridden in competition were so slow as not to require high banking.

The curves of the Louisville and Altham tracks have a banking such that at a speed of a mile in 2 minutes and 53 seconds the wheel is normal to the surface. The superelevation of the Manhattan track was computed for a speed of a mile in 2 minutes and 32 seconds. Fig. 1, page 5, shows the banking of this track, expressed in angles with the horizontal. The curves of the

Racine track, which have the same radii as the Manhattan track, are banked for a speed of a mile in 2 minutes and 26 seconds — a trifle higher speed than for the Manhattan track.

The banking of the Garfield Park track was computed for a speed of a mile in 2 minutes. The angles of the superelevation of this track are shown in Fig. 2 page 7. It is stated that Johnson on this track, in making a worlds record (1:16) of a mile in 1 minute and 49 seconds, leaned slightly toward the inside of the track. Since the banking was figured for a 2 minute gait, the rider going at a speed of 1 minute and 49 seconds would be compelled to lean toward the center of the track to balance the centrifigal force. This shows in a crude way the agreement of theory and practice.

Many short wooden tracks have been constructed with very high banking. Notable among these is a sixth of a mile track opened in Springfield, Mass., in July 1900. The curves (apparently semi-circular) are banked for a speed of a mile in 1 minute

and 20 seconds, the inclination of the surface on the curves being 45° and on the tangents 30° — the steepest track known. This track is pronounced by racing men to be the fastest track in the world.

A summary of the speeds for which the various tracks were constructed is shown in Table IV.

TABLE IV
SPEED FOR WHICH THE BANKING WAS CONSTRUCTED

Name of Track	SPEED	
	Feet per Second	Time for one mile
Waltham & Louisville	30.53	2 min. 53 sec.
Manhattan	34.24	2 " 34 "
Racine, Wis.	36.17	2 " 26 "
Garfield Park	44.00	2 " 00 "
Springfield Mass.	66.00	1 " 20 "

It is obvious that the choice of the velocity to be used depends upon experience and judgement, and not upon mathematical relations. If the track is to be used for motor racing without competition, the velocity should be high, perhaps 66 feet per second, or a mile in 1 minute and 20 seconds; but if the track is to be used for races of

competition without motor pacing, this velocity should be about 44 feet per second, or a mile in 2 minutes.

The values shown for the writer's design, Fig. 5, page 19, are computed for a velocity of 48 feet per second or a mile in 1 minute and 50 seconds. Should the speed vary materially from this value, the wheel will not stand exactly normal to the surface and hence will have a tendency to slip. The tires of a wheel will not slip unless the angle between the plane of the wheel and the normal to the track is greater than the angle of repose. Experiments by the writer gave a value for the angle of repose of a bicycle upon a cement sidewalk of 23° 15' and practically the same value for a smooth wooden surface. Therefore there will be no danger of the wheel's slipping, if the speed be increased until the wheel leans 23° inside of the normal to the track, or if the speed be decreased until the wheel inclines 23° outside of the normal. For the track in Fig. 5, page 19,

the position of the wheel corresponds to a speed of a mile in 1 minute and 12 seconds, and the second to a mile in 4 minutes and 53 seconds. The former is the speed of the fastest steam-motor cycle, and the latter is slower than any probable bicycle race. Therefore, if the superelevation of the track shown in Fig. 5 is adjusted for a speed of 45 feet per second or a mile in 1 minute and 50 seconds, it can be used for considerably faster races and still be safe for slow races and amateur riding. However it will not be possible to attain the highest speed unless the superelevation is adjusted approximately for that speed, since otherwise part of the rider's attention and effort is required to balance his wheel.

It is the practice of some designers to compute the banking for one speed and then construct the track with an arbitrary fractional part of the computed value. For example, the banking of the Manhattan track was nominally computed for a 2 minute pit, and then constructed

with a superelevation equal to 60% of the computed value. The actual banking is that required on a 2 minute and 34 seconds of it.

Mr Hawley, formerly engineer for the Pope Bicycle Manufacturing Co., who has given considerable attention to the design of bicycle-race tracks, suggests that the surface of the tracks on curves be concave as shown in Fig. 7.

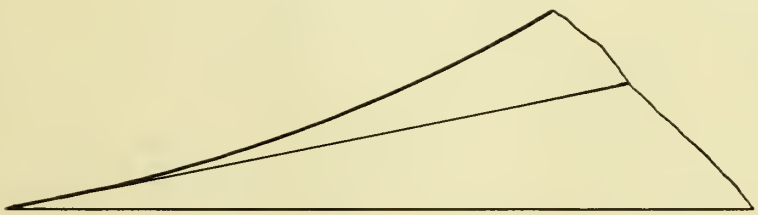


Fig. 7

Such a surface Mr. Hawley claims, would make it easier for one rider to pass another, since to accomplish this he must ride at a higher speed and hence would require a steeper inclination. This conclusion is wrong, since the effect of the increased radius almost exactly counteracts the effect of the increased velocity, requiring therefore the same angle of

inclination. The gauntlet also causes that the concave surface would prevent a rider from flying off the track should he momentarily lose control of his wheel. This advantage is not important, as the banking of most tracks constructed nowadays is sufficient of itself to prevent such an accident. The tendency to "fly the track" may also be lessened by painting parallel guide lines on the surface of the track. This feature was used in the Manhattan track and is described in detail on page 33. However the concave surface would be a disadvantage to a track having low banking. A third objection to the concave surface is that it would be more expensive to construct. Hence the straight surface has been used in the writers design.

3. MATERIALS OF CONSTRUCTION

The surface of a bicycle race-track may be loam, clay, cinders, wood, or cement.

Most of the early tracks were constructed of either loam or clay. Such surfaces are cheap and easy to construct. On the other hand, the cost of maintenance of an earth surface is great, and high banking can not be used, and moisture destroys temporarily the usefulness of the track. The Hamilton Park track was constructed of clay covered with a thin layer of fine brick dust. This track at one time was very popular — but chiefly to its excellent surface.

A surface of cinders is cheap and easy to construct, and is not affected by moisture. However, cinders can not be used with high banking, and such a surface is expensive to maintain, and wounds received by a rider in falling often prove serious.

A well constructed wooden sur-

face is very fast, and its reason has been used on many short tracks, on which super banking is required. An example of such construction is the Colesium track at Springfield, Mass. The surface consists of strips, one inch square, nailed to a foundation of 2"x10" timbers For indoor use where a track must be constructed temporarily wooden construction has decided advantages. For outdoor use wooden tracks are uneconomical because of the destructive action of the elements.

In most of the larger tracks lately constructed, cement surfaces have been used. Such a surface is practically indestructible, hence there is no expense for maintenance. Its usefulness is not destroyed by moisture, and any degree of smoothness may be obtained. Cement was used in the construction of the Waltham the Louisville, the Manhattan, the Garden Track, and the Racine tracks. The surface of the Manhattan is most nearly

ideal and for that reason were de-
scribed somewhat in detail. As is
shown in Fig. 8 the embankment is
composed of four distinct layers: viz,

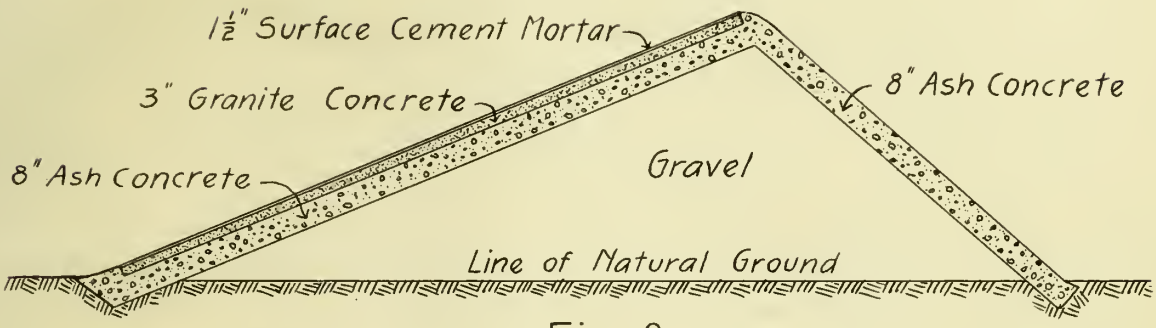


Fig. 8.

a gravel embankment; second, an 8-inch
layer of ash concrete; third, a 3-inch lay-
er of coarse granite concrete; and fourth,
a top layer of 1½ inches of cement mor-
tar. The gravel was deposited in thin
layers and thoroughly compacted by roll-
ing. The purpose of the ash concrete
is to protect the gravel embankment a-
gainst washouts and injury from frost;
and consists of Portland cement and ashes
in the ratio of 1 to 3 or 10. The 3-inch
layer of granite consists of 1 part Portland
cement, 1 part sand, and 7 parts of crushed
granite. The top layer consists of 1½

inches of mortar composed of 1 part Portland cement, 1 part sand, and 2 parts pondered granite. Lamp black was mixed with the mortar to prevent the glare of the sun. The surface of the mortar was roughened by special tools to prevent the slipping of the tires. Special care was taken that the interstices between the blocks of concrete should not be wide enough to impart a vibration to the bicycle. The surface of the Manhattan track has withstood the test of actual practice, as well as the weathering of several years and has proved itself very satisfactory.

A novel feature of this track is the four parallel black guide-lines, each four inches wide, painted on the surface of the track. A racer riding at full speed with his head bent down over the handle bars does not notice that he is approaching the curve, and if he does not guide his wheel according to he will run off the track. The guide lines warn him as he approaches

the curves and thus prevent such an accident.

While the determination of the surface to be used is a matter of judgement, the writer believes that a cement surface such as the Manhattan track will give the best conditions for raising and durability.

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